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by polishing its faces or by applying a reflective coating.

The authors are indebted to Dr. H. Shenker for helpful discussions.

[1] M. Von Stackleburg and P. Paulus, Z. Physik. Chem. B28, 427 (1935). (The others are Zn_3P_2, Zn_3As_2, and Cd_3As_2.)

[2] G. Haacke and G. A. Castellion, J. Appl. Phys. 35, 2484 (1964).

[3] W. Zdanowicz and A. Wojankowski, Phys. Status Solidi 8, 569 (1965).

[4] A. Yariv and R. C. C. Leite, J. Appl. Phys. 34, 3410 (1963).

[5] A. Yariv, *Quantum Electronics* (John Wiley & Sons, New York, 1967), p. 278.

ORIGIN OF FIELD-DEPENDENT COLLECTION EFFICIENCY IN CONTACT-LIMITED PHOTOCONDUCTORS*

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It has been established that diffusion of photogenerated carriers into the electrode can be an important limitation of the collection efficiency of surface-barrier-limited photoconductors.

In barrier-limited photoconductive devices a surface barrier between the metal contact and the conduction or valence band of the semiconductor inhibits injection of carriers. This allows an electric field E applied across the photoconductor to terminate on the metal electrode rather than on charge carriers in the photoconductor. If electron–hole pairs are created near the electrode, carriers of one sign are swept across the photoconductor and collected. This process should give rise to one collected charge carrier for every electron–hole pair generated (i.e., unity collection efficiency).

It has been frequently observed that the collection efficiency η is less than unity and varies with electric field. We have made detailed measurement of the collection efficiency on insulating α-monoclinic selenium and have demonstrated that the observed decrease in collection efficiency is a direct result of the diffusion of photogenerated carriers into the metal electrode. The exceedingly short relaxation times of hot carriers in metals is responsible for the absence of carrier storage effects in Schottky barrier diodes. This relaxation time forces the density of both holes and electrons at the metal–semiconductor interface to be essentially zero. Under all conditions the carrier distribution created by the light must be spread by diffusion. The carrier sink provided by the metal contact keeps the gradient toward it steep and accentuates diffusion toward the contact, while the bias field drifts the entire distribution away from the contact (for carriers of the sign which cross the crystal).

When electron–hole pairs are created near the metal–semiconductor interface by a short burst of light, one can observe the resultant pulse of collected charge. For a uniform electric field, the behavior of this pulse can be divided into three cases. Figure 1(a) illustrates the case in which the collection efficiency is unity and all of the carriers cross the sample without becoming deeply trapped. (A deep trap is one for which release time is much

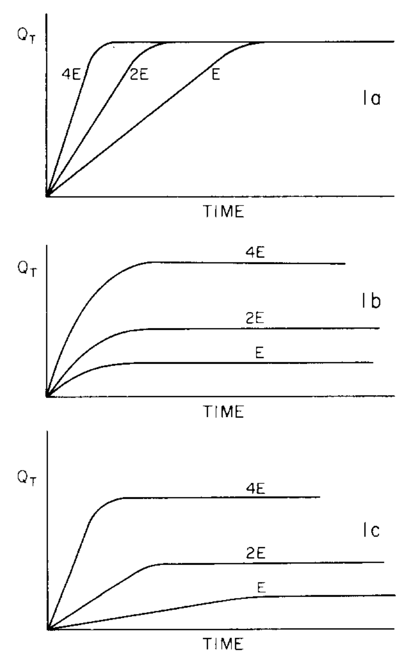

Fig. 1. Collected charge vs time for three cases. (a) Collection efficiency unity and transit time inversely proportional to electric field. (b) Transit time equal to the bulk trapping time and the collection efficiency proportional to electric field. Both inverse transit time and collection efficiency proportional to electric field.

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longer than the carrier transit time.) In this case, the transit time τ_t is inversely proportional to the electric field, and the total collected charge is constant.

If the carriers are deeply trapped while crossing the sample, the rise time of the pulse is equal to the bulk trapping time, independent of electric field, but the collected charge is proportional to the electric field because increasing the field increases the distance the carrier travels before being trapped. This case is illustrated by Fig. 1(b).

In the case to be discussed here, both the inverse transit time and the collected charge are proportional to the electric field, as illustrated in Fig. 1(c).

A number of models have been proposed to explain data of this type. Tabak and Warter[1] have developed a model based on field aided thermal release from bound states. This model predicts an efficiency which increases exponentially with temperature.

A number of authors[2] have discussed recombination in the region of generation. In wide band gap semiconductors, one would expect carriers of one polarity to become trapped. A carrier of the other sign would then recombine with the trapped carrier. Since the electric field drifts the more mobile species away from the less mobile, a higher field would decrease the time in which recombination can occur and raise the collection efficiency.

A model similar to that of recombination is one in which both carriers are trapped in a narrow layer near the surface. This model predicts a collection efficiency which is exponentially dependent upon the product of the mobility μ and the trapping time in the damaged layer of the carrier crossing the sample.

Although any or all of the above mechanisms may be operative, they are often unimportant compared with the effect of diffusion of carriers into the contact. The fraction of generated carriers lost by this process can be evaluated quantitatively by solving the continuity equation for the carrier density $n(x, t)$,

$$\frac{\partial n}{\partial t} = \mu\left(\frac{kT}{q}\,\frac{\partial^2 n}{\partial x^2} - E\,\frac{\partial n}{\partial x}\right) \tag{1}$$

under the boundary conditions $n(0, t) = n(d, t) = 0$ and the initial condition

$$\begin{aligned} n(x, 0) &= N_0 \exp(-\alpha x) && x > 0 \\ &= 0 && x \leq 0\,, \end{aligned} \tag{2}$$

where the illuminated interface is at $x = 0$, the collecting contact is at $x = d$, α is the optical absorption constant for the incident light, and N_0 is the density of carriers generated at $x = 0+$. This calculation yields

$$\eta = \frac{E/E_f}{1 + E/E_f}\,, \tag{3}$$

where $E_f \equiv \alpha kT/q$ is an "effective diffusion field."

The theory presented here makes a number of predictions beyond the field dependence given in Eq. (3). Since both the drift and diffusion terms in Eq. (1) are linear in the mobility, it is evident that η must be independent of mobility and polarity of carrier. The form of Eq. (3) makes it clear that the efficiency predicted by this theory decreases as temperature and optical absorption constant increase. A further prediction is that the charge which diffuses into the contact does so in a time much shorter than the transit time so that the charge collection pulse should show a linear increase as shown in Fig. 1(c), not the rounded shape as in Fig. 1(b).

Experiments were performed on α- monoclinic selenium platelets with thickness in the range 30 to 60 μ, provided with noninjecting gold contacts. A contact on one side of a platelet was cemented to a copper substrate with silver paste. A 10-nsec light pulse centered in wavelength around 4200 Å was shown through a semitransparent electrode on the opposite side of the platelet. Since the optical absorption constant α in selenium at 4200 Å is 2×10^5 cm^{-1}, the carriers were all generated within about 0.05 μ of the surface.[3] Carriers of one sign (dependent upon the polarity of the bias field) drifted across the sample with transit time of the order of 10^{-6} sec. The current caused by this moving charge was integrated, amplified, and displayed on an oscilloscope screen. The observed waveforms were similar in shape to those shown in Fig. 1(c) as expected. Variation of the polarity and magnitude of the the bias field, intensity of the light, and temperature of the sample allowed the behavior of the quantum efficiency to be investigated. Over the range of experimental conditions reported here, the magnitude of the collected charge was proportional to the intensity of the light pulse and much less than the charge induced on the contacts by the bias field, indicating that space-charge effects were negligible.

The variation of the inverse transit time and magnitude of the collected charge with electric field E for a typical sample is shown in Fig. 2. These data were taken with fixed light intensity. The solid curve in Fig. 2(b) is the efficiency given by Eq. (3) with the vertical scale adjusted to fit the data at 7 kV/cm. The collection efficiency at 1 kV/cm fixed bias decreased about 10% as the temperature was increased from 0°C to 50°C in good agreement with predictions of the diffusion theory. The field assisted thermal release theory predicts that the efficiency should *increase* by a factor of 2 over this temperature range for a trap depth of 0.1 eV. The observed efficiencies for carriers of both signs were nearly identical despite a difference of an order of magnitude between the measured bulk mobilities of holes and electrons. If the efficiency were limited by trapping in a damaged surface layer, the products of the mobilities and the trapping times in the damaged layer $\mu\tau_{tr}$ for carriers of the two polarities would have to be nearly equal. Even with the most favorable assumptions, recom-

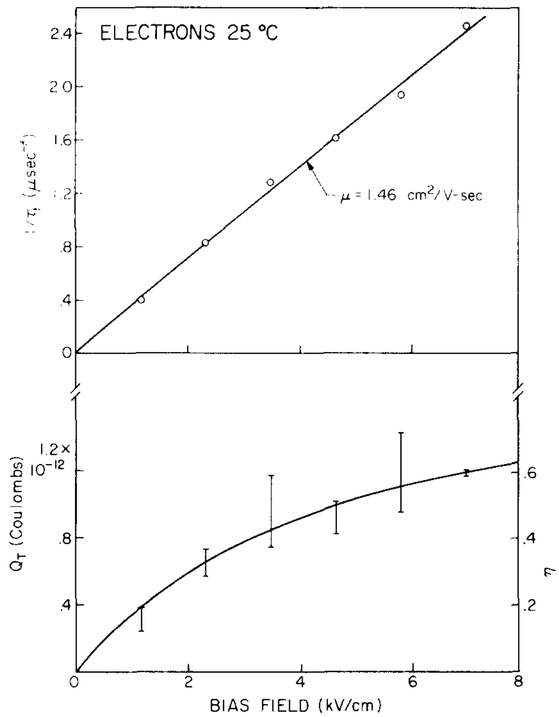

Fig. 2. Inverse transit time and total collected charge for fixed light intensity as a function of applied electric field. Measured points are electrons in α-monoclinic Se. The solid curve on the lower plot is the theoretical dependence [Eq. (3)].

bination in the generation region is too small to explain the observed results by about two orders of magnitude.

We have shown here that in the case that a metal contact forces the carrier concentration at the metal–semiconductor interface to nearly zero, diffusion can be an important limitation on the efficiency of a photoconductive device. Since diffusion occurs with all mobile carriers, the efficiency derived for these considerations should be considered the maximum obtainable from contact-limited devices with any additional effects acting to further decrease the efficiency.

It should be clear that limitations imposed by this effect are important in a number of semiconductor devices such as surface-barrier photodiodes and nuclear particle detectors.

The authors wish to sincerely thank Dr. J. W. Mayer and T. C. McGill, Jr., for many helpful discussions.

[1] Mark D. Tabak and Peter J. Warter, Jr., Phys. Rev. 173, 899 (1968).

[2] Cf., H. C. Built and H. E. Wegner, Rev. Sci. Instr. 34, 274 (1963); W. L. Brown, IRE Trans. NS-8, 2 (1961); J. W. Mayer, *Nuclear Electronics* (Organization for Economic Cooperation and Development, European Nuclear Energy Agency, Paris, 1964), p. 129.

[3] J. M. Caywood and J. D. Taynai, J. Phys. Chem. Solids (to be published).

NONLINEAR EFFECTS OF LASER PROPAGATION IN DENSE PLASMAS

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Two nonlinear effects of laser propagation in dense plasmas have been analytically investigated, viz., laser penetration into an overdense plasma and the self-focusing of a laser beam. It is concluded that for laser powers currently being used, both these effects can be quite important.

Linear theories of electromagnetic wave propagation in plasmas have well established that transverse waves with a frequency less than the plasma frequency cannot propagate in a plasma. This may also be readily seen from an expression for the real part of dielectric constant, which for weakly collisional plasmas may be written as

$$\mathrm{Re}(\epsilon) \approx (1 - \omega_p^2/\omega^2) \ . \tag{1}$$

For $\omega < \omega_p$, ϵ becomes negative and the wave cannot propagate in the plasma. Now it is well known that plasmas produced by the laser irradiation of solid particles have a plasma frequency typically greater than the incident laser frequency. In order to understand the laser penetration and heating of such plasmas therefore, one either has to take account of the diffuse nature of the vacuum–plasma interface[1] or invoke some kind of nonlinear effects.[2] Kaw and Dawson[2] have recently proposed a nonlinear relativistic effect which could explain the penetration of extremely intense laser pulses in overdense plasmas; the laser pulse has to be intense enough to cause the directed component of electron velocity to be comparable to the velocity of light. We wish to discuss here another nonlinear penetration effect which can occur at considerably lower laser powers. Physically, the nonlinearity arises because of the velocity dependence of collision frequency and becomes important as soon as the di-